Investigation of the Effects of Facility Background Pressure on the Performance and Voltage-Current Characteristics of the High Voltage Hall Accelerator

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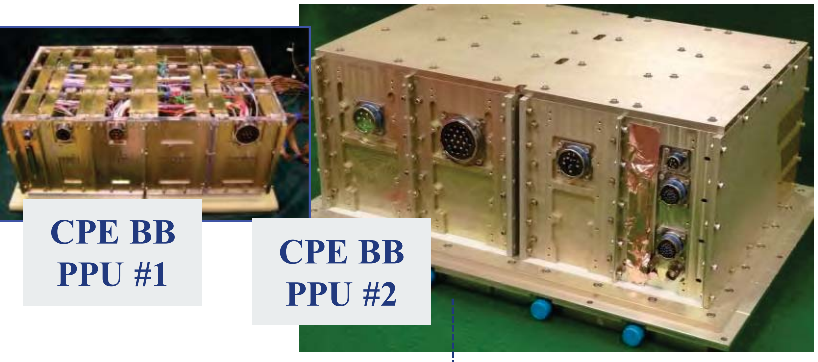
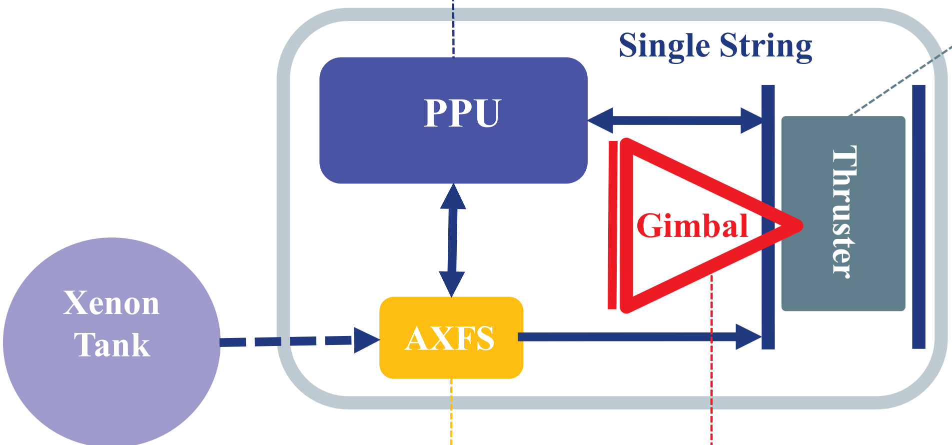
HiVHAc System Layout

IEPC-2013-445

- The HiVHAc project has leveraged OCT SBIR funding to advance the HiVHAc thruster system readiness
- Extensive atmospheric and vacuum testing of the Colorado Power Electronics (CPE) brassboard PPU #1 has been performed at NASA GRC
- NASA GRC plans to perform SDT and LDT testing of the CPE BB#2/EDU PPU with the HiVHAc EDU 2 thruster





- The HiVHAc engineering development unit (EDU) 2 thruster offers improved performance and mission benefits over SOA
- The HiVHAc EDU2 thruster has undergone extensive performance evaluation and has completed a random vibration test
- Recent test with the HiVHAc EDU2 thruster indicate that a throughput of over 10,000 kg can be attained without the need for the in-situ discharge channel replacement mechanism, thus further simplifying thruster design

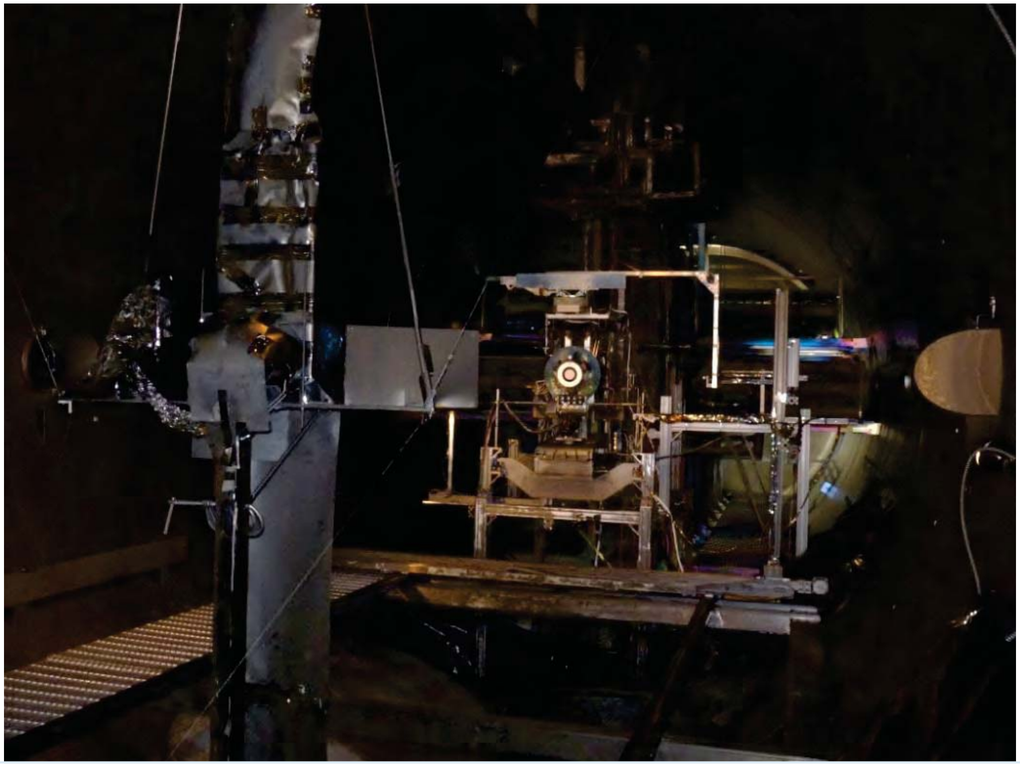
VACCO XFCM

Gimbal (derived from NEXT)

- The HiVHAc project has leveraged ISPT and DoD/USAF funding to mature the TRL level of a xenon feed system for HiVHAcA flight-qualified VACCO xenon flow control module (XFCM) was delivered to NASA GRC in June 2012 and was integrated with the HiVHAc thruster tests in VF5 and VF12

HiVHAc Test Objectives in NASA Glenn Vacuum Facility 5

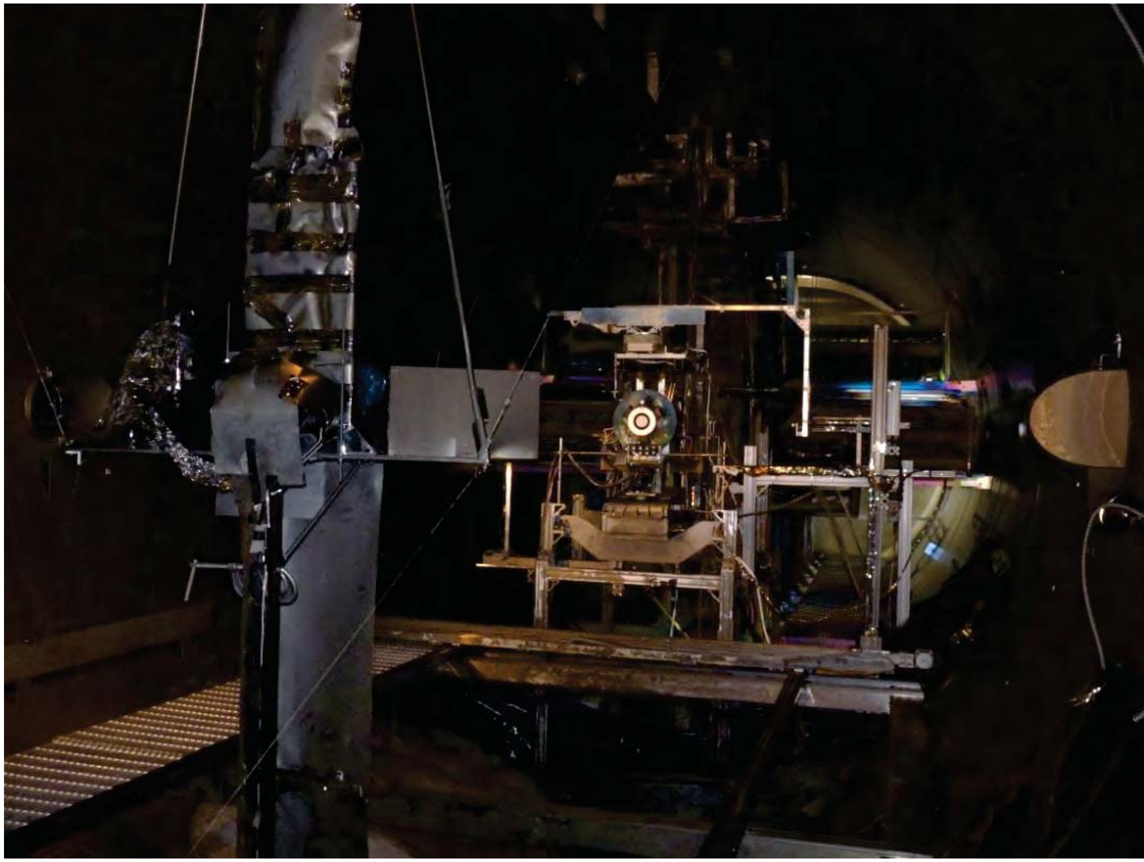
- <u>Objectives of the HiVHAc test in VF5 include:</u>
  - Assess the performance of the HiVHAc thruster with the CPE BB PPU and VACCO XFCM- *IEPC-2013-445*
  - Perform detailed near field polar maps of the ion beam*- *IEPC-2013-058*
  - Assess performance of HiVHAc EDU thruster in the lowest possible attainable background pressure environment and at elevated background pressure
  - Assess impact of varying the background pressure on thruster performance
  - Acquire HiVHAc thruster EDU VI characteristics to assess thruster stability at various operating thruster flow rates and magnet settings



HiVHAc Test Setup in VF5

HiVHAc Test Objectives in NASA Glenn Vacuum Facility 5

- **Additional objectives of the HiVHAc VF5 test include:**
  - Measure plasma properties in the near field plume using AFRL high speed Langmuir probes (HSLP), *AIAA-2014*
  - Perform Fast Camera measurements to characterize thruster operating modes, *AIAA-2014*
  - Assess impact of changing cathode flow split and auxiliary flow injection on thruster operation and performance, *AIAA-2014-*
  - Evaluate thruster performance at different cathode positions (cathode#2), *AIAA-2014*



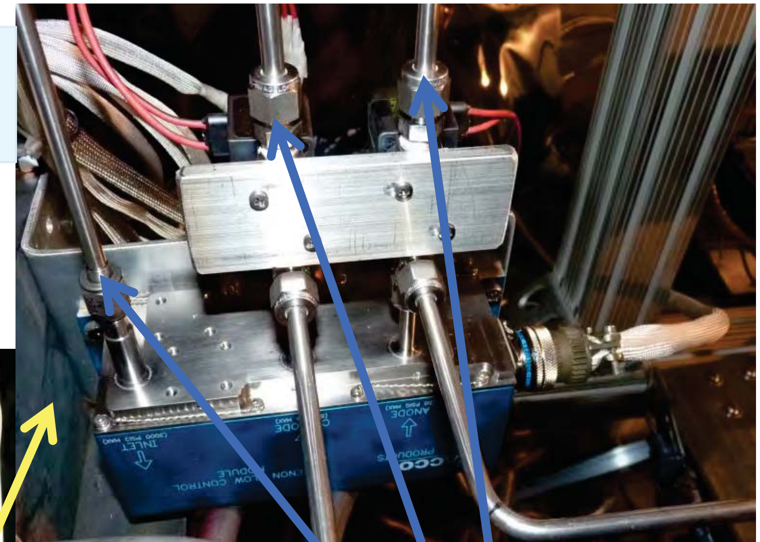
- Perform detailed thermal characterization of the HiVHAc thruster using thermocouple and IR camera (Aerospace Corp) measurements

HiVHAc VF5 Test Configuration

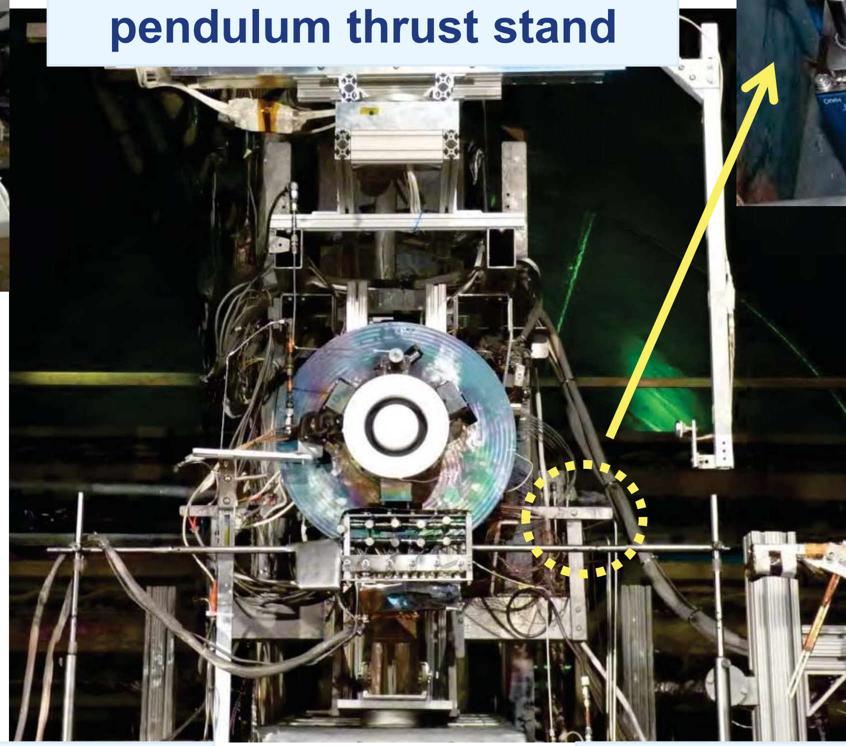
Configuration in NASA Glenn Vacuum Facility 5

CPE BB PPU outside VF5

VACCO XFCM inside VF5



HiVHAC mounted inside VF5 on inverted-pendulum thrust stand



Laboratory power supplies for V-I test

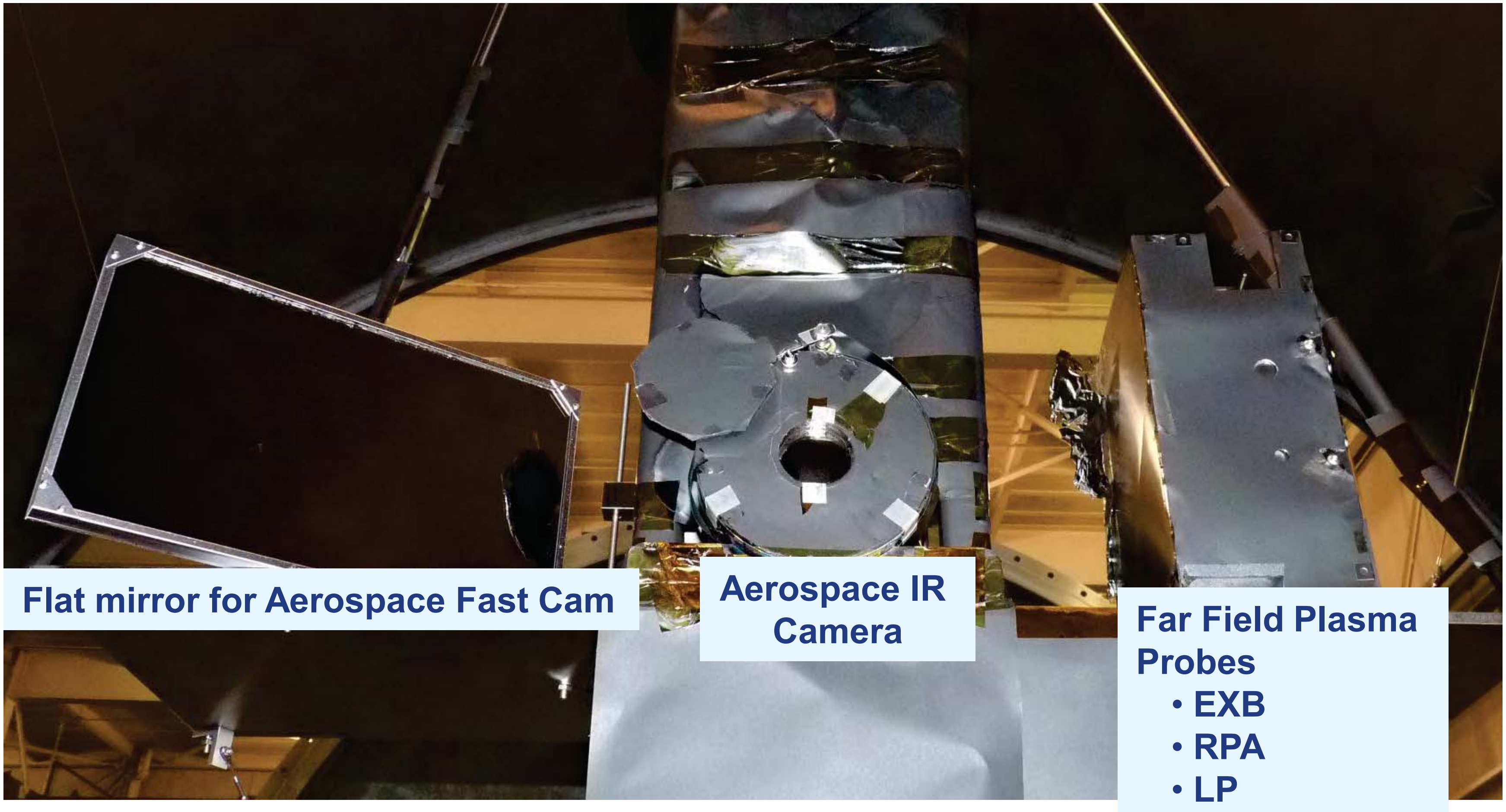
MFCs that supply xenon to XFCM and Thruster

HiVHAc VF5 Test Configuration
Configuration in NASA Glenn Vacuum Facility 5

- **Plasma diagnostics includes AFRL high speed Langmuir probes (HSLP) that are situated on radial and axial stages**

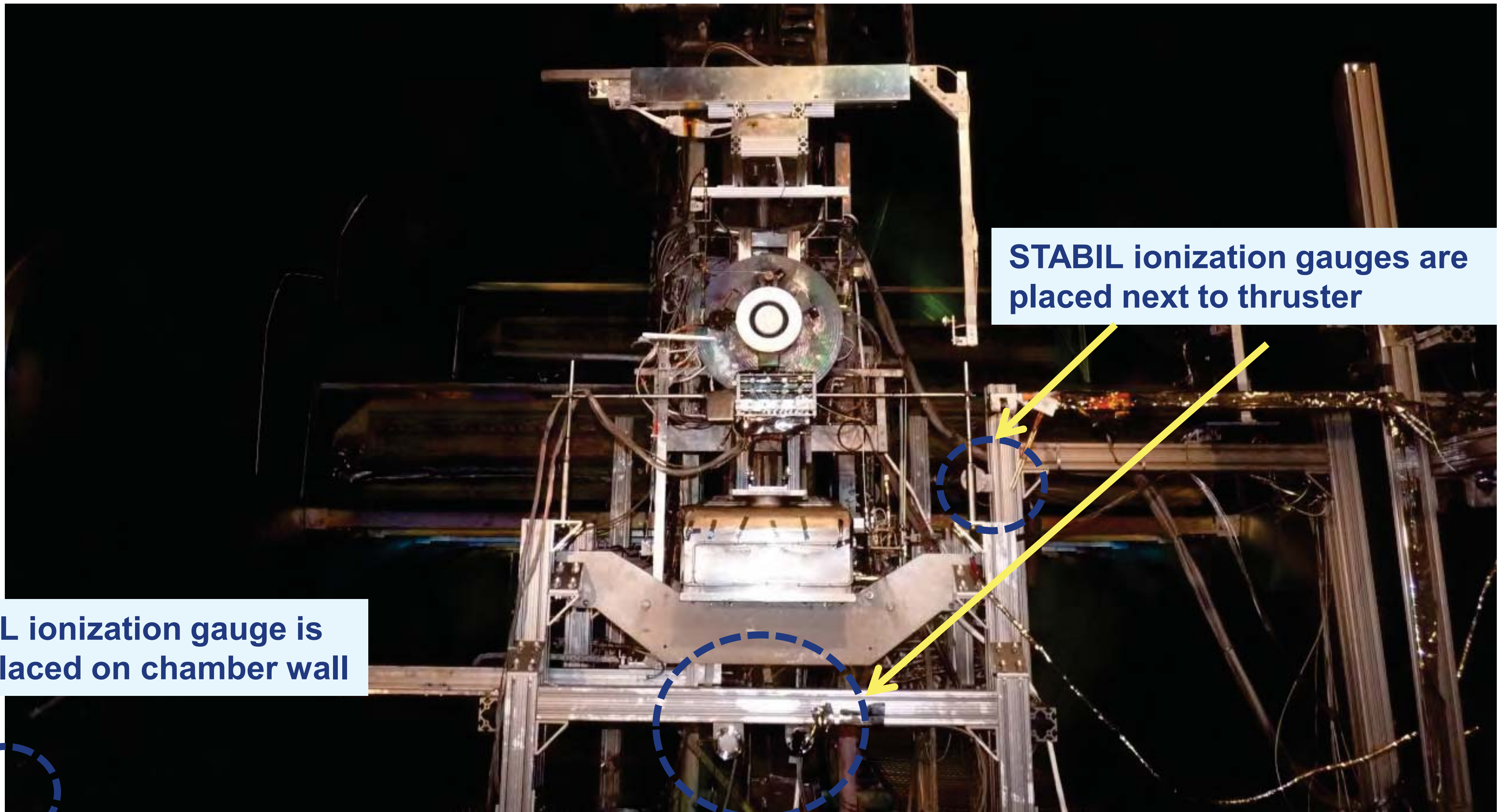
HiVHAc VF5 Test Configuration

Configuration in NASA Glenn Vacuum Facility 5 – (p4 of 5)



- Far field diagnostics includes an IR camera, fast camera, and plasma probes (EXB, RPA, LP)

HiVHAc VF5 Test Configuration
Configuration in NASA Glenn Vacuum Facility 5 – (p5 of 5)



STABIL ionization gauges are placed next to thruster

STABIL ionization gauge is also placed on chamber wall

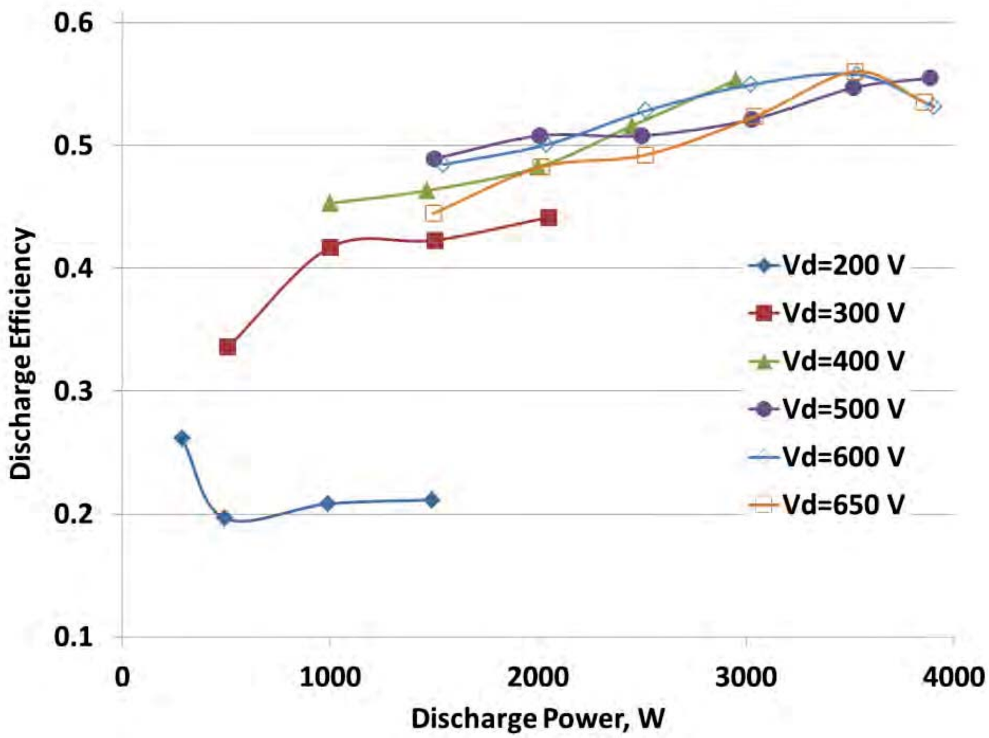
Performance Characterization of HiVHAc in VF5

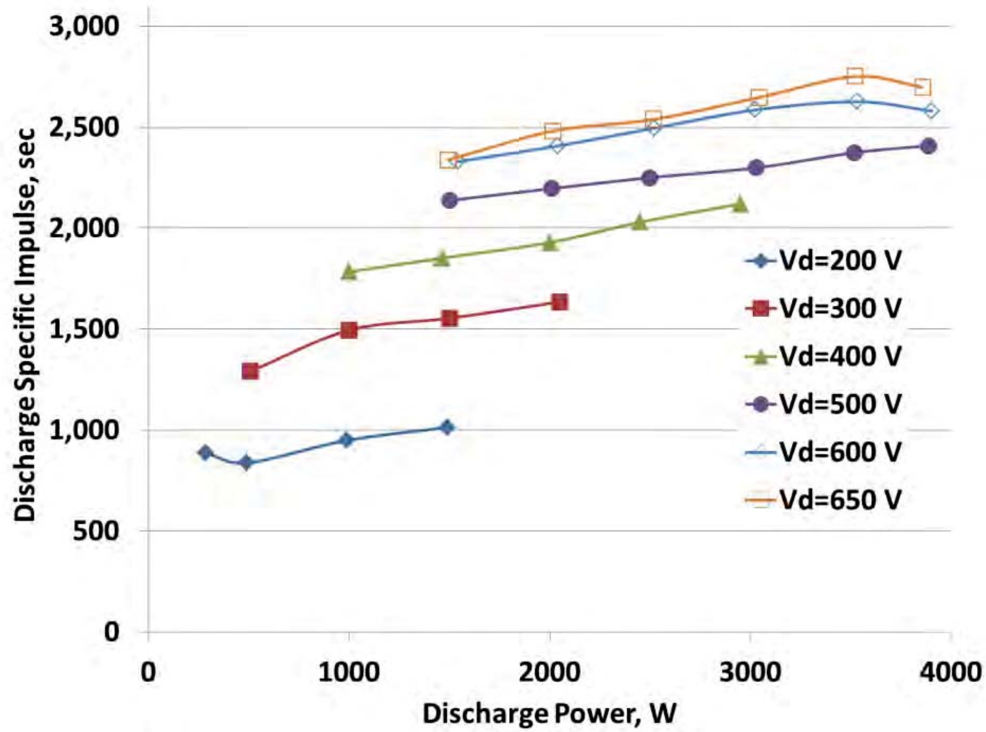
- Performance characterization of the HiVHAc thruster was performed for the proposed HiVHAc throttle table

- In general, performance evaluation results indicate a drop in performance (3-8%) at the lowest background pressure condition when compared to previous VF12 performance results

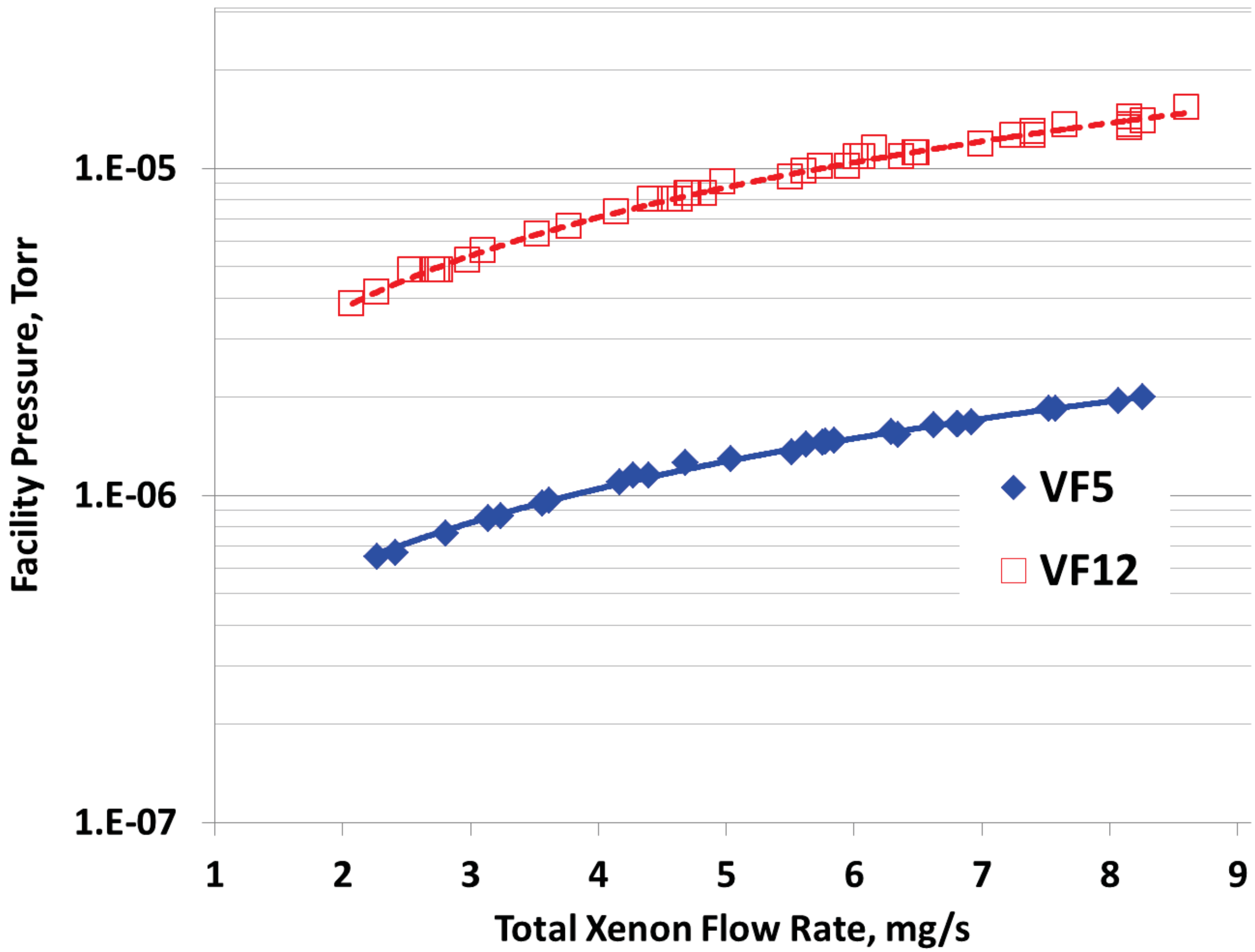
	Power, W								
Vd, V	300	500	1000	1500	2000	2500	3000	3500	3900
200	X	X	X	X					
300	X	X	X	X	X	X			
400*			X	X	X	X	X	X	X
500			X	X	X	X	X	X	X
600			X	X	X	X	X	X	X
650			X	X	X	X	X	X	X

Performance Characterization of HiVHAc in VF5 Indicated Performance Levels Lower than VF12

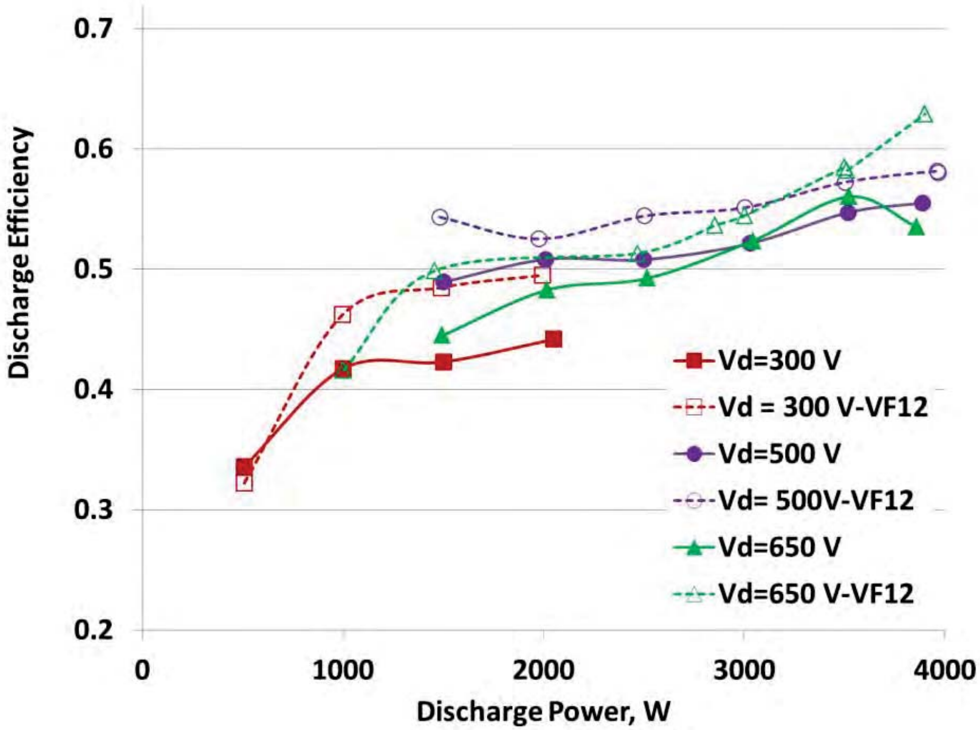


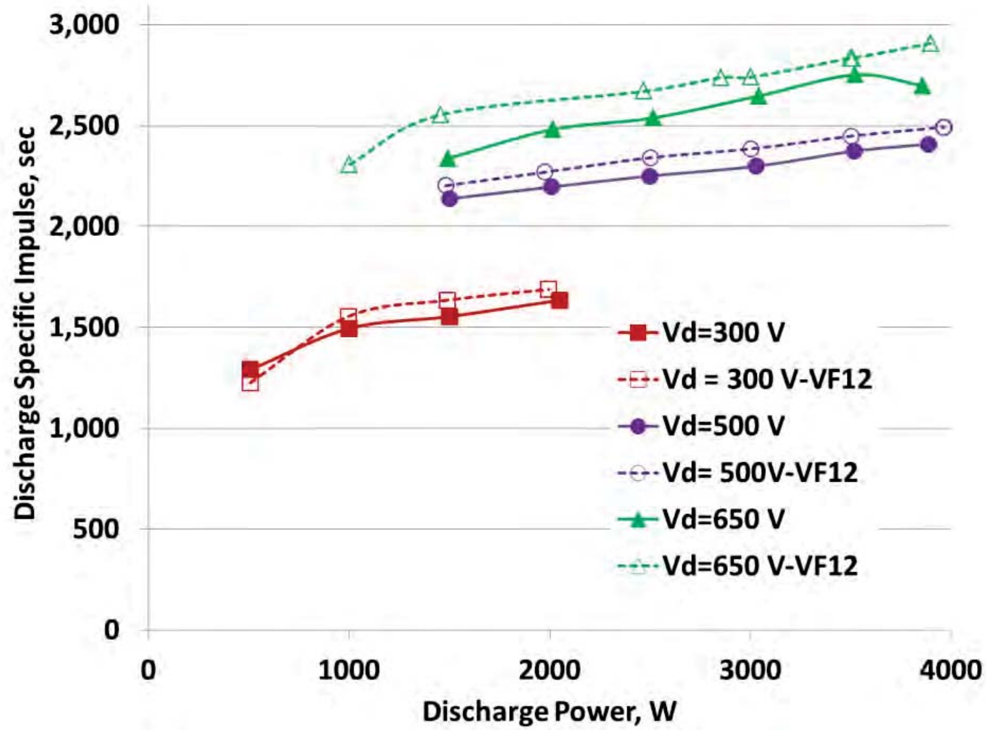


Background Pressure Near the Thruster was Approximately 6× lower in VF5 when Compared to VF12



Performance Characterization of HiVHAc in VF5 Indicated Performance Levels Lower than VF12



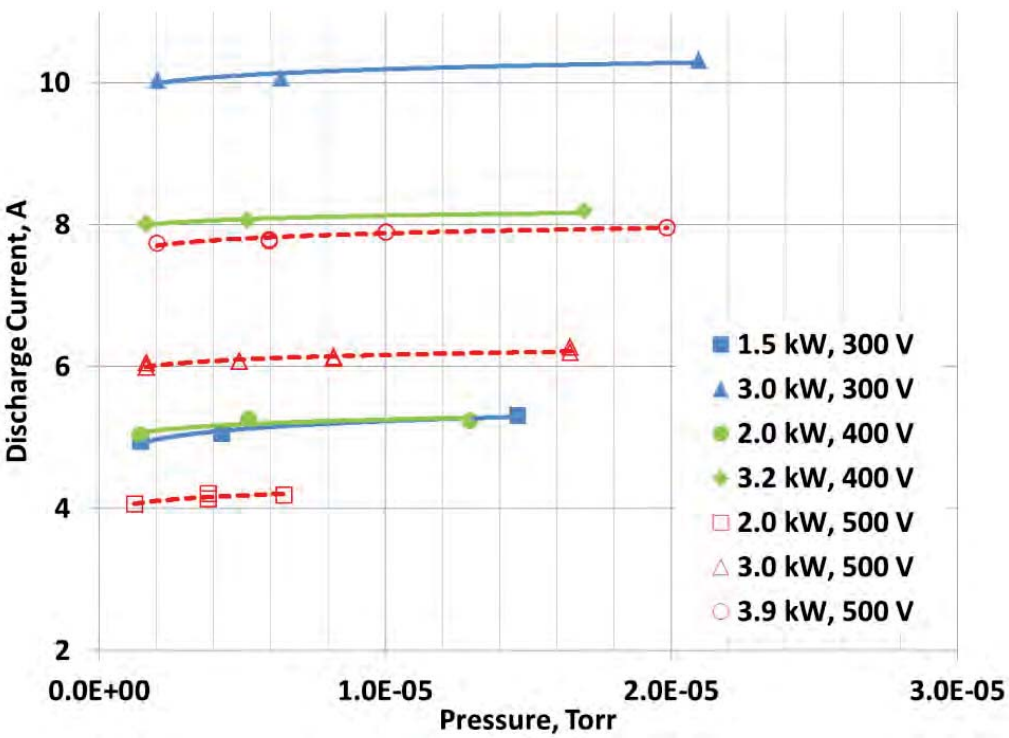


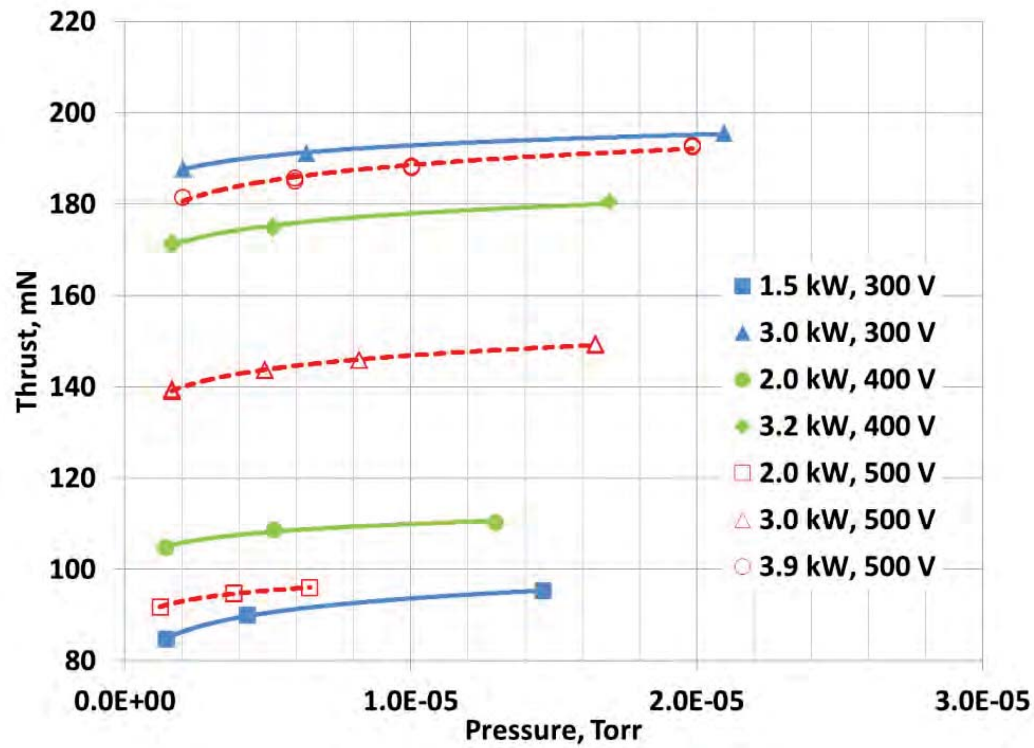
Pressure Sensitivity Study was Performed at Selected Thruster Operating Conditions

Discharge Voltage, V	Discharge Power, kW	Pressure, Torr
300	1.5	1.1×10^{-6}
300	3.0	1.8×10^{-6}
400	2.0	1.2×10^{-6}
400	3.2	1.7×10^{-6}
500	2.0	1.2×10^{-6}
500	3.0	1.7×10^{-6}
500	3.9	2.0×10^{-6}

- No tests at elevated background pressure conditions were performed at 600 and 650 V due to sharp increase in the thruster's discharge current when the facility background pressure was increased
- Increasing the background pressure at 600 and 650 V resulted in the discharge moving upstream towards the anode, that caused "glowing" of the erosion zone tip and increase discharge current magnitudes.

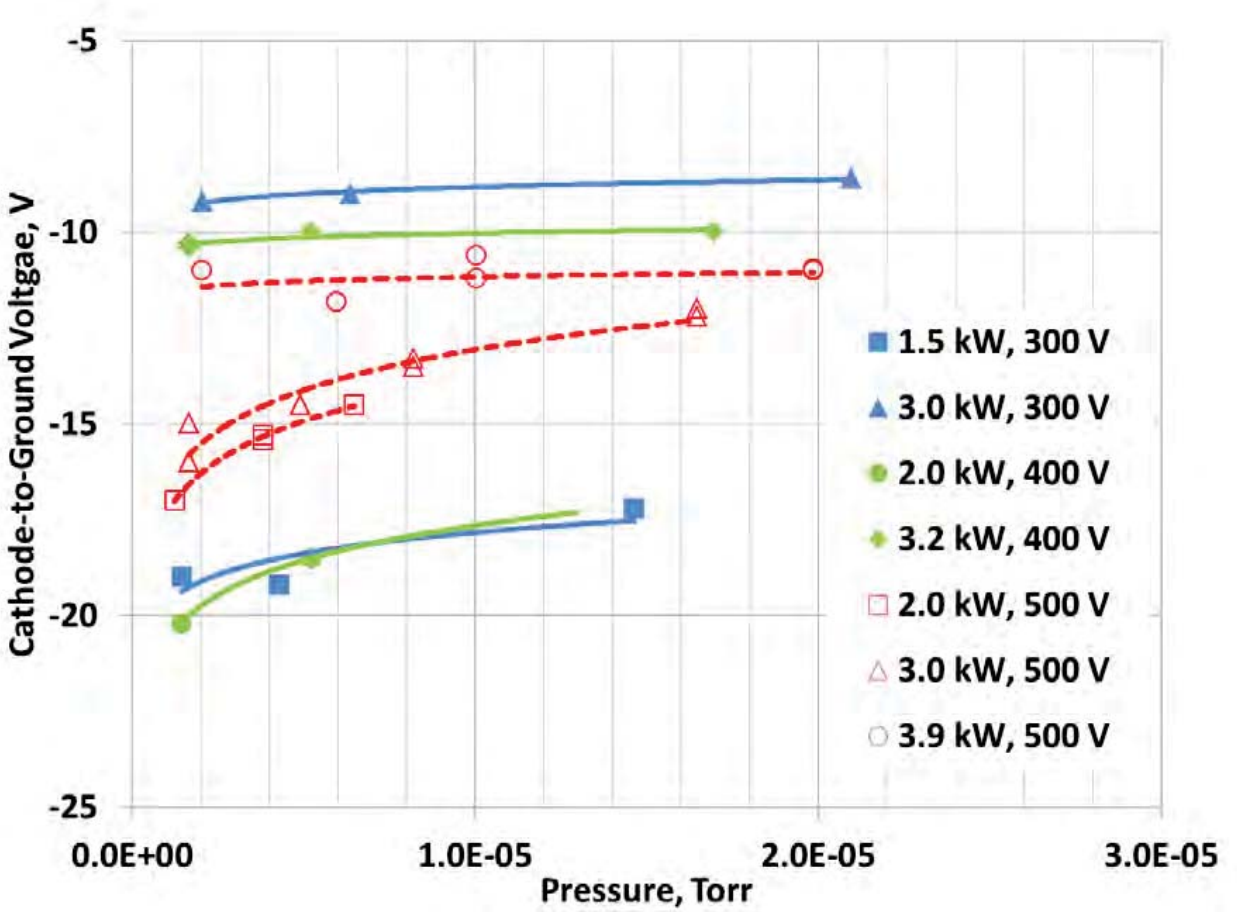
Variation of Discharge Current and Thrust with Background Pressure





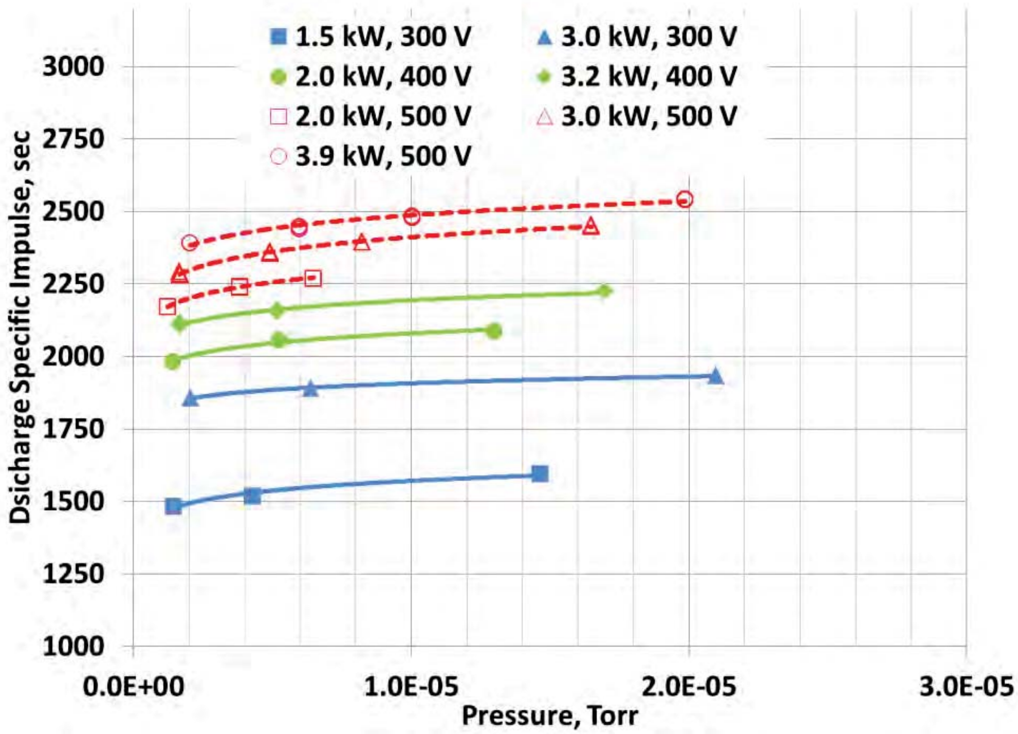
Discharge current and thrust increased as the background pressure was increased

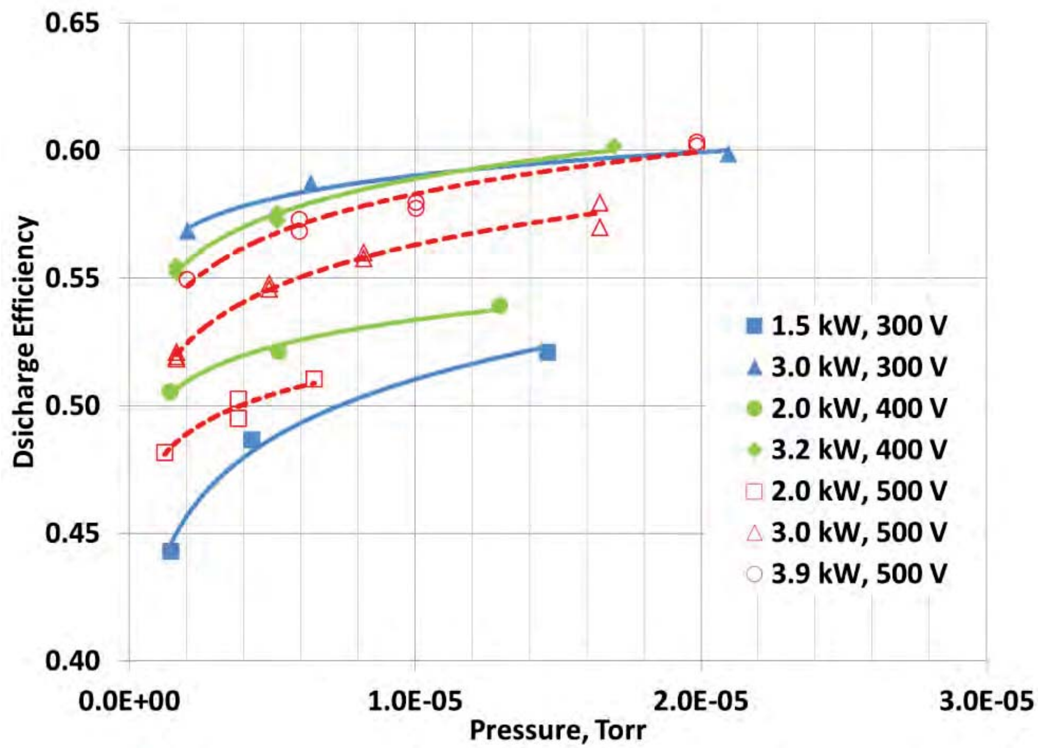
Variation of the Cathode Coupling Voltage with Background Pressure



Cathode coupling voltage became more positive as the background pressure was increased

Specific Impulse and Thrust Efficiency Variation with Background Pressure





Both discharge specific impulse and efficiency increased as the background pressure was increased

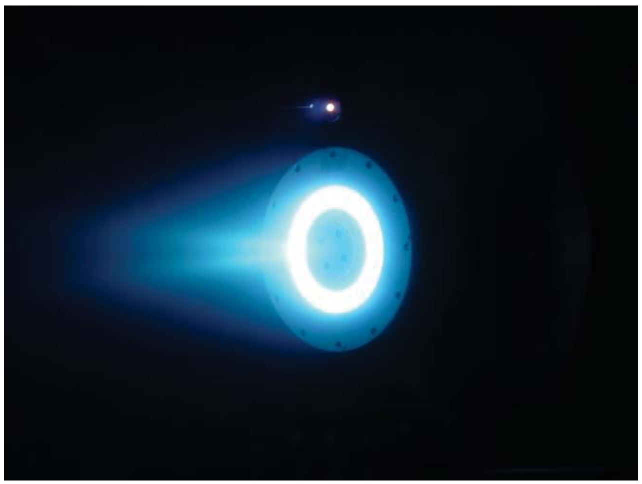
Increasing the Background Pressure Improved the Thruster's Performance

Summary of Pressure Sensitivity Evaluation

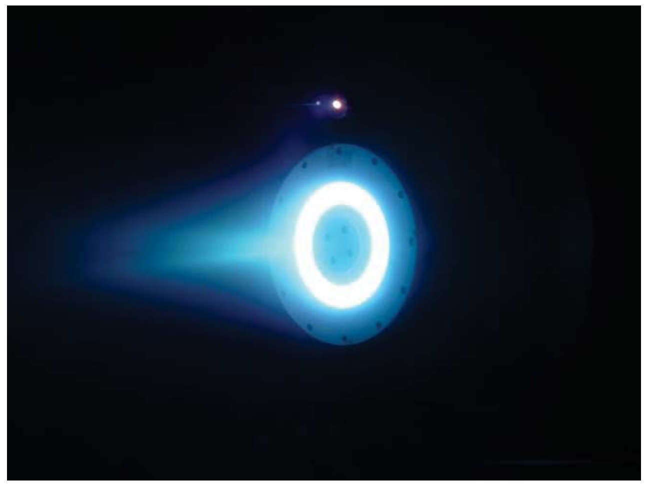
Test Condition	$3\times P_0$				$10\times P_0$			
	I_d/I_{d0}	T/T_0	I_{sp}/I_{sp0}	η/η_0	I_d/I_{d0}	T/T_0	I_{sp}/I_{sp0}	η/η_0
300V 1.5kW	1.020	1.060	1.060	1.098	1.070	1.120	1.120	1.175
300V 3.0kW	1.003	1.018	1.018	1.033	1.030	1.041	1.041	1.053
400V 2.0kW	1.040	1.037	1.037	1.031	1.040	1.053	1.053	1.067
400V 3.2kW	1.004	1.020	1.020	1.035	1.020	1.050	1.050	1.085
500V 2.0kW	1.028	1.031	1.031	1.035	1.030*	1.046*	1.046*	1.060*
500V 3.0kW	1.005	1.029	1.029	1.054	1.030	1.069	1.069	1.095
500V 3.9kW	1.006	1.041	1.041	1.075	1.030	1.082	1.082	1.134

Thruster Operating at 400 V and 6 mg/s

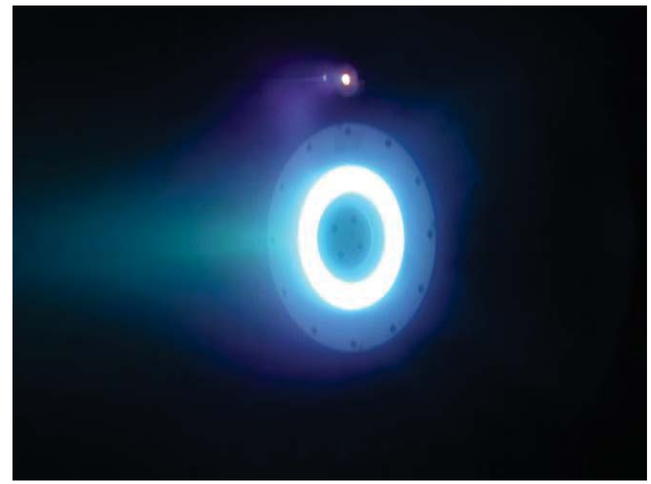
3x Pressure



10x Pressure



24x Pressure



Thruster plume structure changed as the background pressure was increased

Fast V-I Characteristics of the HiVHAc Thruster were Performed at Various Thruster Operating Conditions

- The V-I profiles of the HiVHAc EDU thruster were obtained for various thruster flow rates and electromagnet settings at different facility background pressures.

- The V-I profiles were measured to assess how the thruster operation and stability is affected by operation at elevated background pressure conditions.

- The HiVHAc EDU thruster V-I characterization was acquired for anode flow rates of 2, 3, 4, 5, 6, 6.5, and 7 mg/s for electromagnet currents magnitudes of Io, 1.5·Io, and 2·Io.

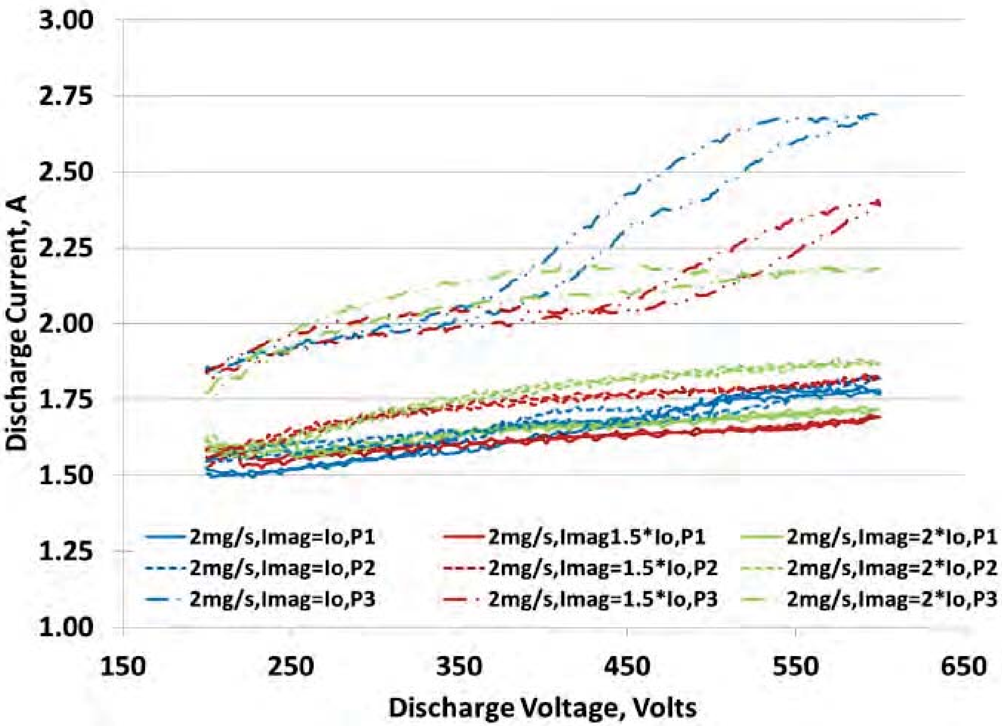
- For all test conditions, the thruster discharge voltage was varied between 200 and 600 V at 1 V increments with a voltage ramp rate of 1V/s.

Fast V-I Characteristics of the HiVHAc Thruster Provide a Preliminary Assessment of Operational Stability

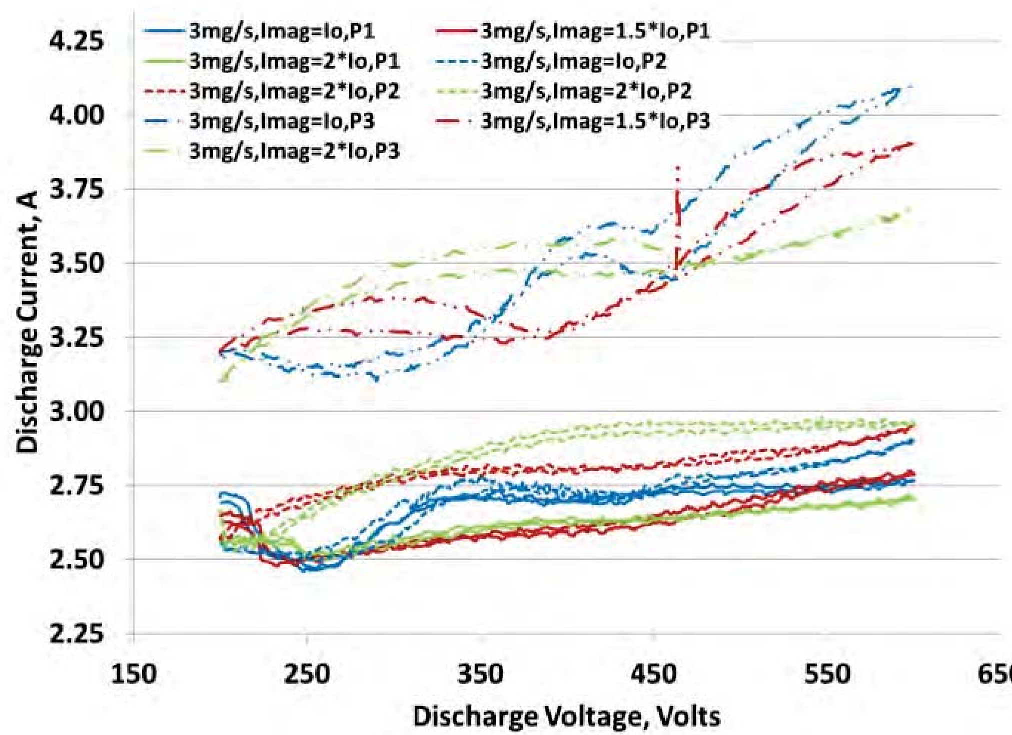
- The V-I profiles provide insights into thruster behavior and stability
  - A negative sloped region where as the discharge voltage is increased the discharge current decreases (negative impedance); in this region it was observed that the thruster discharge current oscillations were large;
  - A flat region where as the discharge voltage is increased the discharge current, for the most part, was unchanged; this region was characterized by relatively small discharge current oscillations and is desirable;
  - A positive sloped region where as the discharge voltage is increased the discharge current increases (positive impedance); in this region the discharge current oscillations magnitude was relatively greater than the flat region but was less than their magnitude in the negative region; and
  - A hump region where the discharge current increases rapidly with the discharge voltage in a narrow voltage region, this typically resulted in large magnitude discharge current oscillations.

V-I Characteristics: 2 and 3 mg/s, 200-600 V

2 mg/s

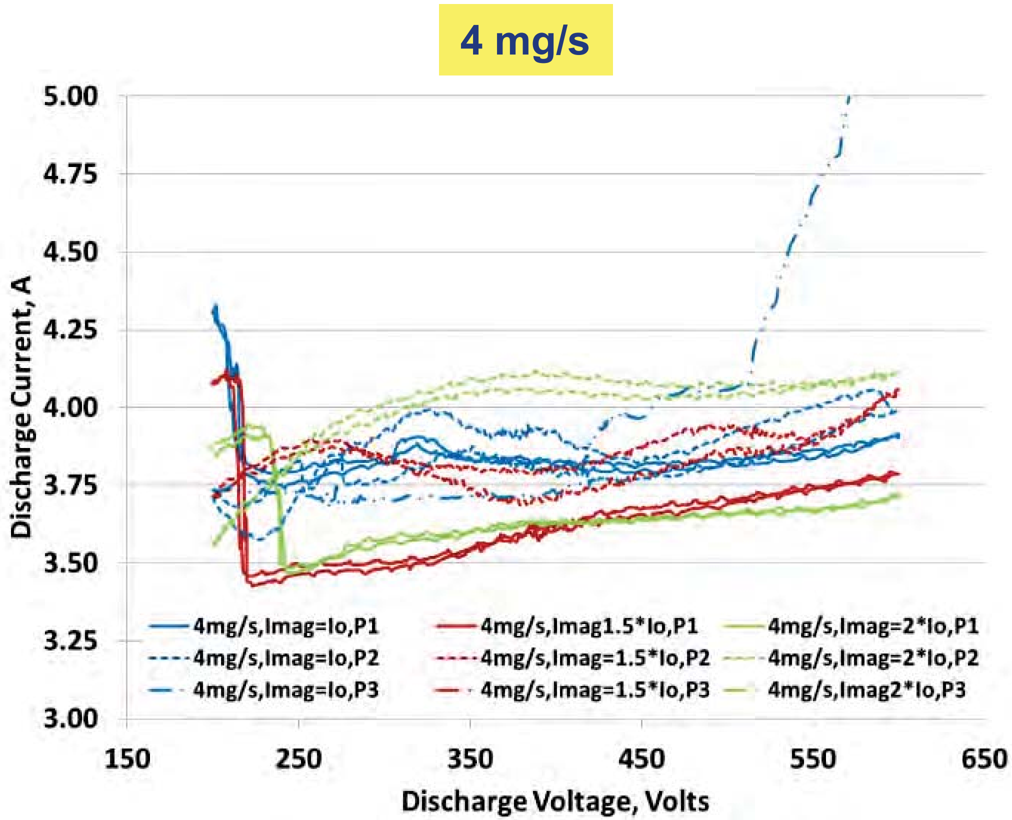


3 mg/s



Thruster operation is most stable at the lowest operating facility background pressure

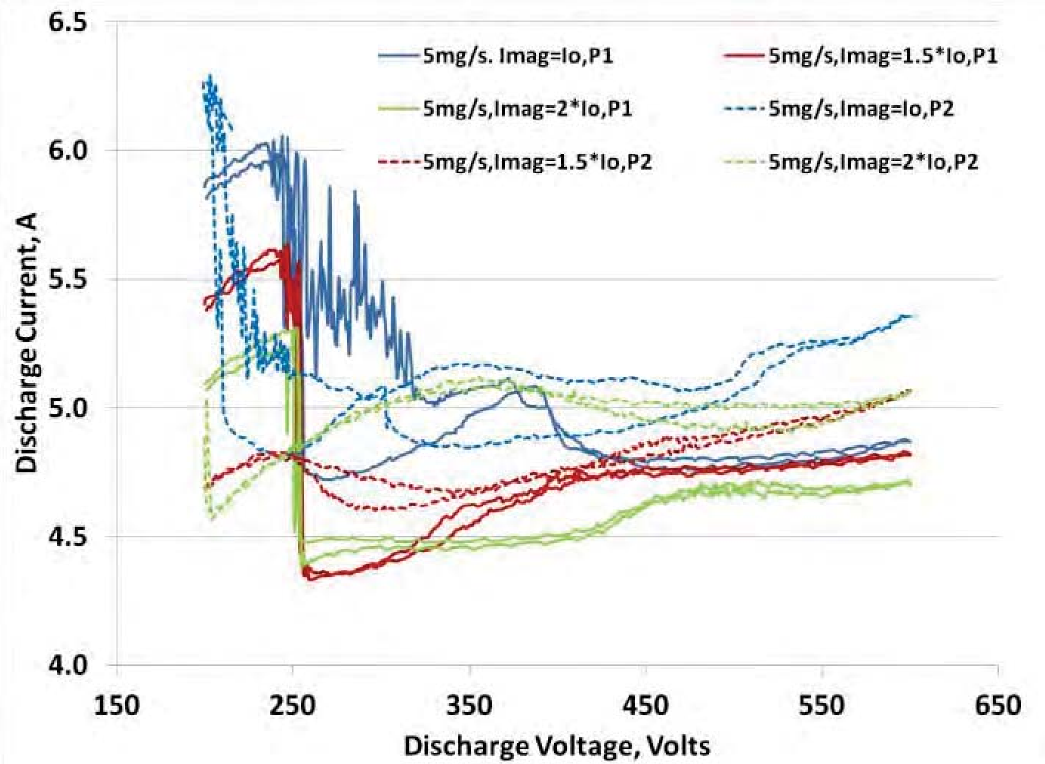
V-I Characteristics: 4 mg/s, 200-600 V



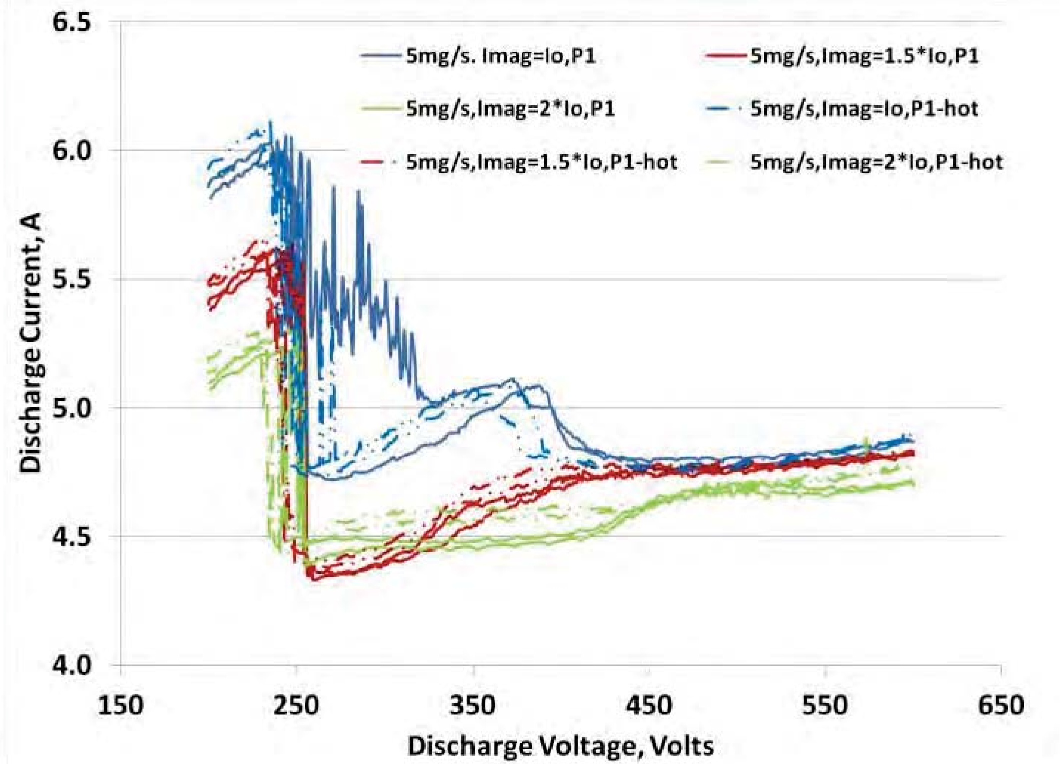
Thruster operation is most stable at the lowest operating facility background pressure

V-I Characteristics: 5 mg/s, 200-600 V

5 mg/s

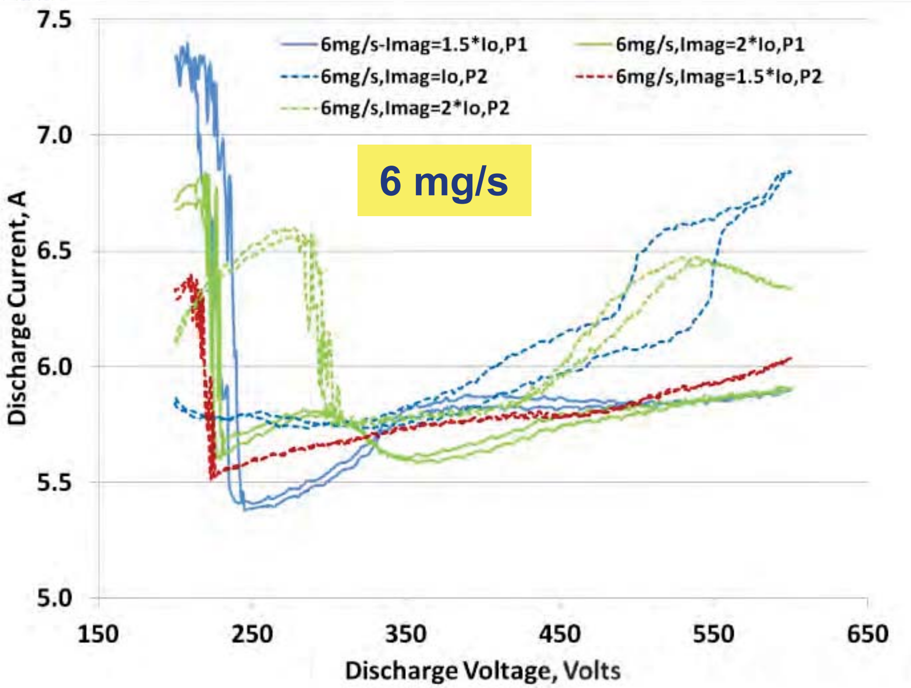


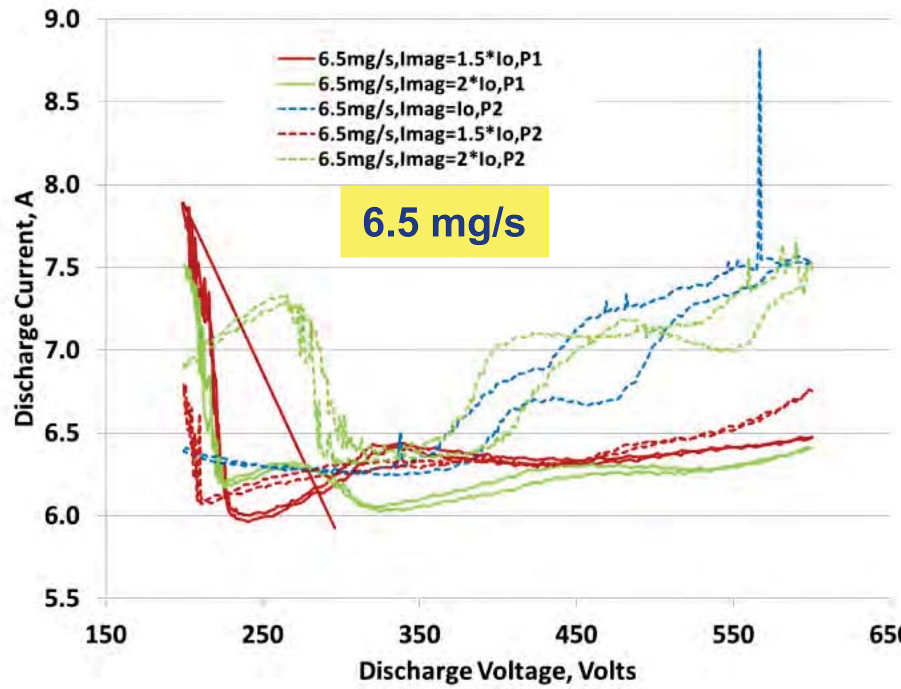
5 mg/s - hot

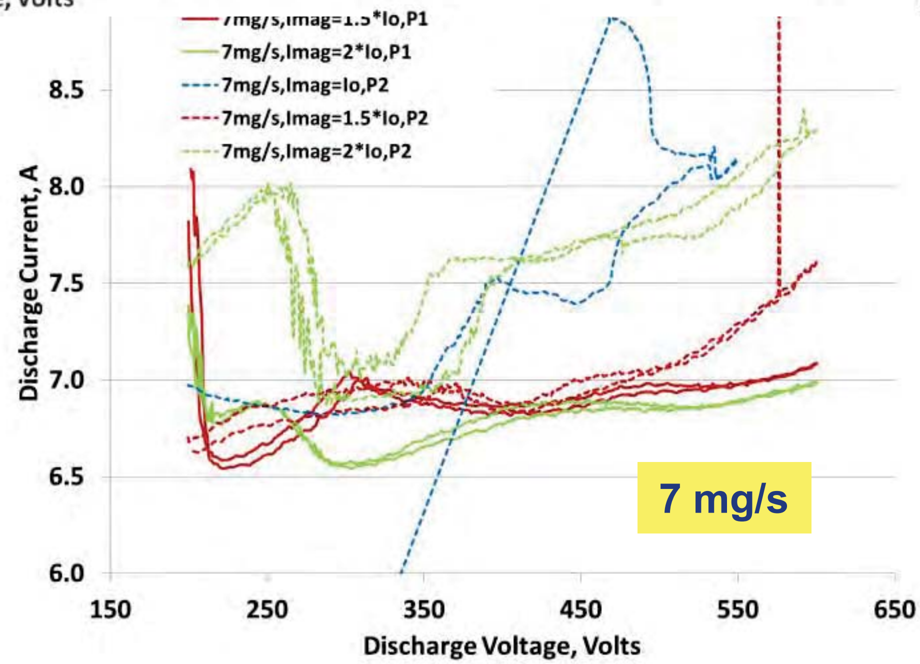


- Thruster operation is most stable at the lowest operating facility background pressure
- BN temperature did not impact V-I Characteristics

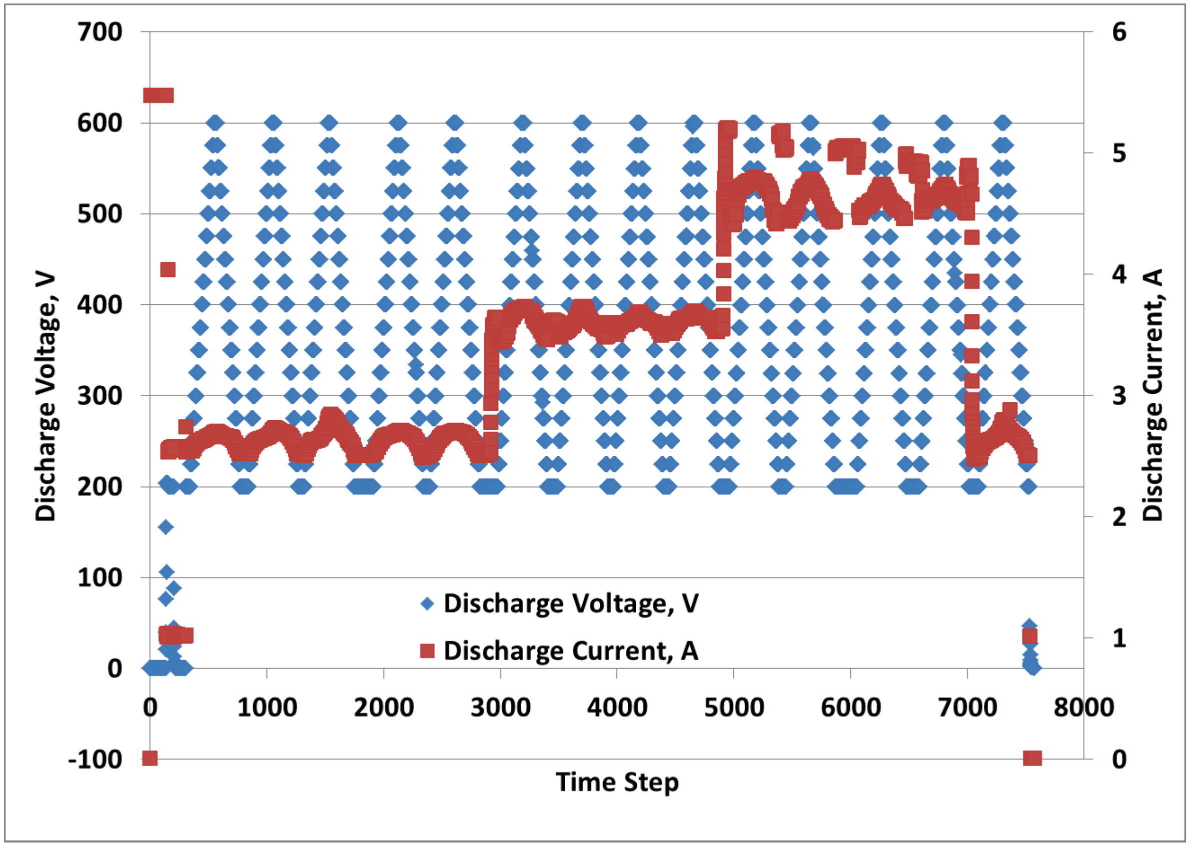
V-I Characteristics: 6, 6.5, 7 mg/s, 200-600 V







Slow V-I Characteristics of the HiVHAc Thruster were Performed at Different Operating Conditions to Map Thruster Performance



Utilize the slow V-I sweeps as a way to perform a quick map of the thruster performance

- **Voltage step 25 V, Time at each Voltage 30 sec, record all thruster telemetry including thrust**
- **Perform sweeps at different anode mass flow rates and different magnet setting**

Summary & Conclusions

- Analysis of the test results is indicating that the HiVHAc thruster exhibits reduced performance at lowest attainable background pressure condition when compared to performance results obtained during performance tests in VF-12 (~6× higher background pressure than VF-5)

- Test results found that flow ingestion does not account entirely for the change in thruster performance at the elevated background pressure levels

- Experimental results indicated that the cathode-to-ground voltage magnitudes changed as the facility background pressure was varied. This indicated that the coupling between the cathode and thruster's discharge was changing.

- Experimental evidence that the ionization and acceleration zones were shifting upstream towards the thruster's anode were also observed in this test series.

- The thruster's V-I profiles results indicated that the region of stable thruster operation narrowed as the facility background pressure was increased.

Future Work

- Performance characterization in the reconfigured VF5 at facility background pressure of approximately 1×10^{-6} Torr during full power thruster operation;
- Performance characterization at constant power;
- V-I characterization;
- Thermal characterization using thermocouples and an IR camera;
- Plume characterization using faraday, E×B, and retarding potential analyzer probes;
- FAST camera measurements of the thruster operating modes;
- Inner and outer discharge channel surface Langmuir probe measurements to help ascertain the location of the discharge ionization and acceleration zones;
- Investigation of cathode position and flow fraction effects on thruster performance; and
- Investigation of impact of magnetic circuit topology on thruster operation at various facility background pressure levels.